AMORE: AN AUTONOMOUS CONSTELLATION CONCEPT FOR ATMOSPHERIC AND OCEAN OBSERVATION

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ABSTRACT

The **Atmospheric Moisture and Ocean Reflection Experiment**—AMORE—is a proposed constellation of microspacecraft for atmospheric and ocean observation. AMORE would observe **atmospheric radio occultations** and **ocean reflections** from an array of 12 or more microspacecraft to support climate process studies and the testing and refinement of climate models. The spacecraft would track the L-band signals of 48 **GPS** and GLONASS satellites, directly and reflected off the ocean, and would exchange occultation crosslinks at 10, 14, 18, and 23 GHz to map tropospheric water vapor from the surface to the tropopause, the detailed refractivity and thermal structure of the global atmosphere, and difficult-to-observe eddy-scale changes in ocean circulation. GNSS

1. INTRODUCTION

With the completion of the Global Positioning System constellation and the appearance of increasingly affordable spaceborne receivers, GPS is moving rapidly into the world of space flight projects. Applications of spaceborne GPS to Earth science include centimeter-level precise orbit determination (POD) for ocean altimetry; Earth gravity model improvement and other enhancements to GPS global geodesy; high resolution 2D and 3D ionospheric imaging; and atmospheric limb sounding (radio occultation) to recover precise profiles of atmospheric density, pressure, temperature, and water vapor distribution. Figure 1 offers a summary of the Earth science emerging from spaceborne GPS.

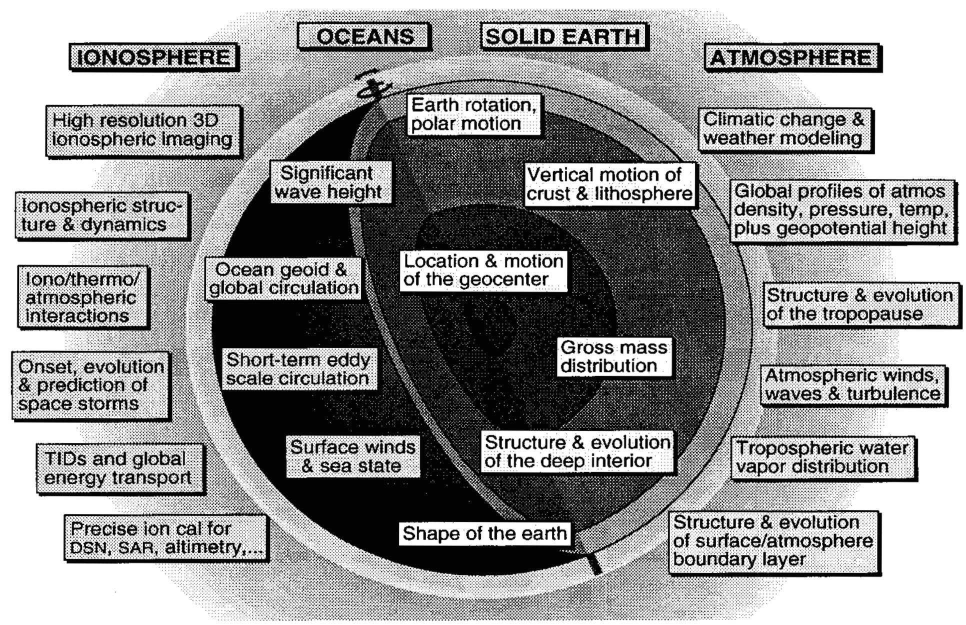

Fig. 1. Some key science applications for a spaceborne array of GPS receivers.

2. GPS ATMOSPHERIC OCCULTATION

The probing of planetary atmospheres by radio occultation dates to the early 1960s when Mariners 3 and 4, viewed from Earth, passed behind Mars [1, 2]. In this technique a radio signal from a spacecraft moving behind a planet is tracked until blockage. As the signal cuts through the planet's refractive atmosphere, its lengthening path delay, revealed by the observed change in phase delay or Doppler shift, can yield a precise profile of the atmospheric density, pressure, temperature or moisture, geopotential heights, and, depending on the frequencies involved, to some degree composition and winds. Amplitude variations can expose atmospheric turbulence and wave structure.

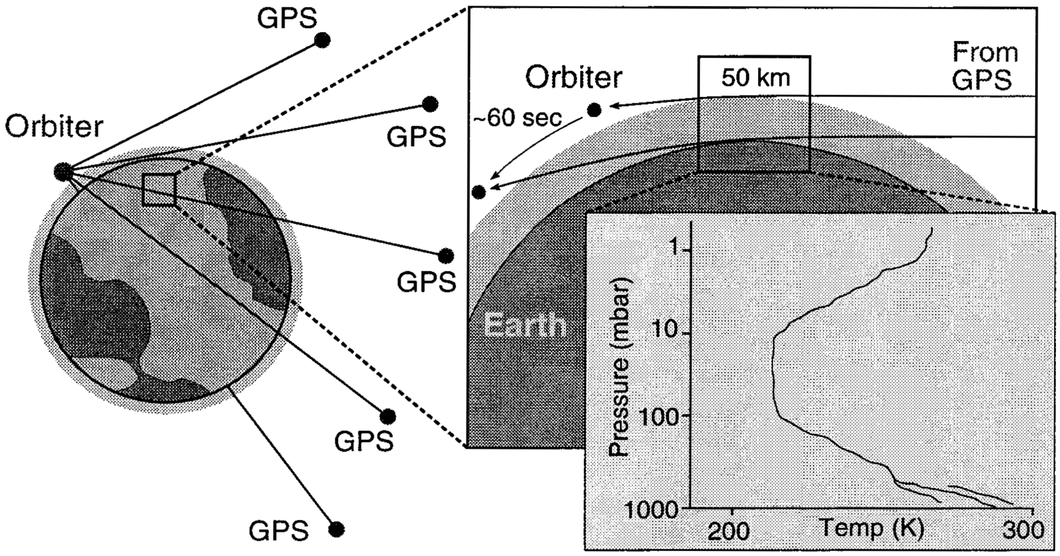

Fig. 2. Illustration of atmospheric temperature profiling by GPS occultation

While radio occultation has probed many planets and moons throughout the solar system, it has as not yet found operational application to Earth, for two reasons. First, the observation requires both a radio source and a suitable receiver off the planet, outside the atmosphere; seldom have we had such matched pairs in Earth orbit. Second, to be of use in studying Earth's atmosphere, the nature of which we know well, such measurements must be continuous, comprehensive, synoptic. We therefore need many transmitters and receivers aloft at once, densely sampling the global atmosphere every few hours. Until the arrival of GPS and low cost microspacecraft, the evident cost of such an enterprise made it impractical within Earth science programs.

In the late 1980s, a group at JPL proposed observing GPS signals from space to make atmospheric soundings by radio occultation, as shown in Fig. 2 [3]. Briefly, the observed Doppler shift in the GPS signal induced by atmospheric bending permits accurate estimation of the atmospheric refractive index. From that one can retrieve, in sequence, profiles of the atmospheric density, pressure, and temperature (or, in the lower troposphere, water vapor) with high accuracy (<1 Kelvin in temperature) and a vertical resolution of a few hundred meters [4, 5]. Figure 3 shows the predicted accuracy of atmospheric temperature profiles as a function of altitude, based on extensive simulation studies performed at JPL. Notice that in the lower part of the troposphere, the uncertainty in water vapor content, particularly in the tropics, leads to a large error in the recovered temperature. In that region, since it is water vapor that is of greater consequence in weather modeling, it becomes advantageous to adopt nominal temperature lapse rates and instead recover water vapor profiles.

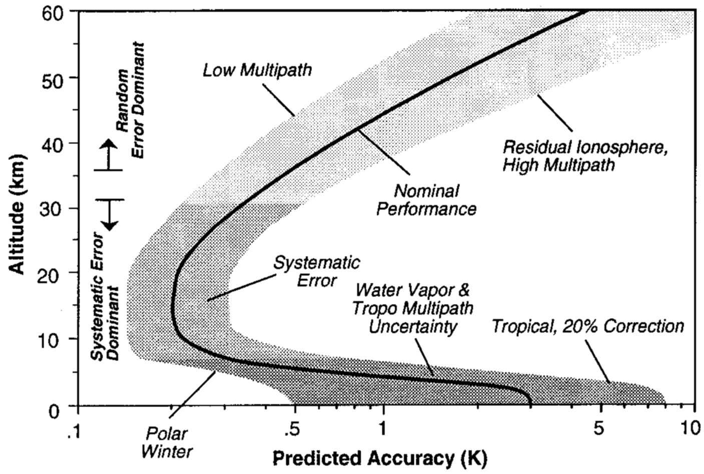

Fig. 3. Estimated GPS-derived atmospheric temperature accuracy vs altitude.

A single satellite can recover more than 500 profiles each day, distributed almost uniformly around the globe; a large constellation would recover many thousands of profiles, which could one day have a profound impact on both long term climatological studies and short term weather modeling. In addition, such an array would enable high resolution 3D tomographic imaging of the ionosphere (see next section) and would serve many geodetic uses (e.g., gravity recovery, geocenter monitoring) as well.

Stimulated by the original proposal, a group led by the University Corporation for Atmospheric Research in Boulder, CO, succeeded in obtaining sponsorship from the U.S. National Science Foundation for a low-cost demonstration experiment called GPS/MET (for meteorology), to fly as an add-on payload to a NASA experiment (an Optical Transient Detector) aboard Orbital Sciences Corporation's MicroLab I satellite. Additional mission support was provided by NOAA (the National Oceanic and Atmospheric Administration) and the FAA (Federal Aviation Administration), and supplemental analysis support was obtained from NASA. To acquire the occultation data, Allen Osborne Associates, manufacturer of the TurboRogue geodetic GPS receiver, developed a ruggedized flight version known as the TurboStar. JPL, a collaborator on the experiment, revamped the receiver software for autonomous operation and occultation scheduling in space. The TurboStar produces 50 Hz dual frequency data samples during occultations using the P-codes when antispoofing is off and less precise alternative methods when it is on.

The MicroLab I was launched successfully aboard a Pegasus rocket in April 1995. While there have been minor problems with the satellite itself, the receiver has performed almost flawlessly from the beginning. Thousands of occultation passes were acquired and analyzed. Figure 4 shows a typical temperature profile, along with nearby radiosonde measurements for comparison. For a more comprehensive presentation of results from this experiment see Refs [6] and [7].

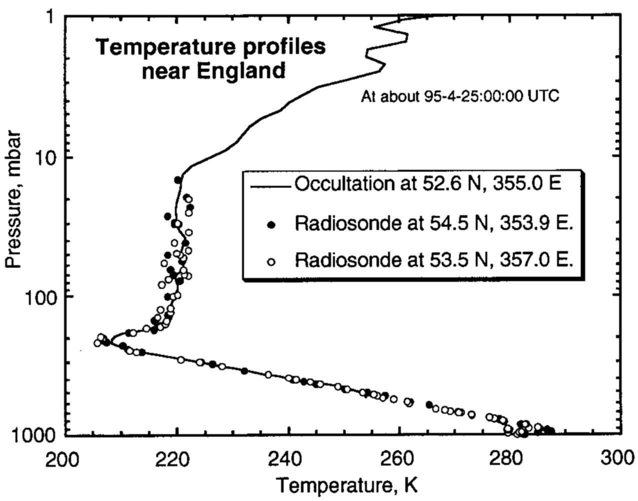

Fig. 4. Typical GPS atmospheric temperature profile compared with two radiosondes.

3. GPS IONOSPHERIC IMAGING

The dual frequency GPS signals offer a direct means of measuring the integrated or total electron content (TEC) along the line of sight from the receiver to the GPS satellites (see [8], for example. Today, ionospheric measurements from the global GPS ground network are used to generate accurate global maps of zenith TEC

[9]. Such maps are valuable both for calibration of tracking data from other satellites and for scientific study of the ionosphere. While ground-based zenith TEC maps represent a big advance in our ability to image the ionosphere, they have their limitations. Horizontal resolution is still relatively crude, though that will improve with more ground sites, and information on the vertical electron distribution is entirely absent. Various efforts have been made to recover vertical information from ground based TEC data by means of two-dimensional tomography, but the basic observing geometry severely limits the vertical resolution that can be achieved [10]. That limitation can be readily removed by the introduction of horizontal cuts through the ionosphere afforded by spaceborne receivers. Much like atmospheric occultations, such observations will slice through the ionosphere to provide exquisite vertical resolution; combined data from large numbers of space- and ground-based receivers will enable high resolution two- and three-dimensional snapshot imaging of the global ionosphere [11].

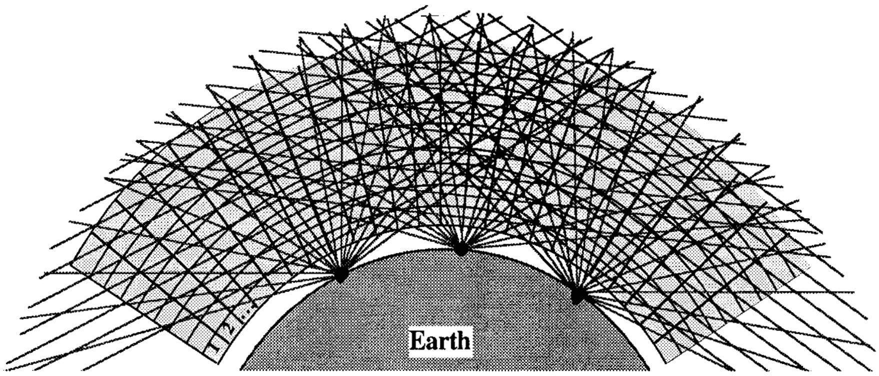

Fig. 5. *Ionospheric sampling with combined ground and spaceborne GPS receivers.*

Figure 5 illustrates in two dimensions the ionospheric sampling that can be achieved from the ground and space. Simulation studies performed by *Hajj et al* [11] demonstrate quite dramatically the value of space-based GPS data in ionospheric imaging. With ground data alone, virtually nothing of the vertical electron distribution is revealed; with space data alone, good quality vertical and horizontal images are recovered. Combining space and ground data provides finer detail and overall resolution, however, the improvement over purely space data is rather slight. This is because in addition to providing the vertically slicing cuts needed to recover vertical information, the space links cross one another over a much wider range of angles, supplying much of the information needed.

4. THE AMORE CONCEPT

The proposed Atmospheric Moisture and Ocean Reflection Experiment—AMORE—would unite several GNSS sensing techniques with advanced microspacecraft technology, and introduce high-frequency radio occultation crosslinks of its own, to provide powerful new atmosphere and ocean data sets for use in climate studies, meteorology, and other Earth science disciplines.

The baseline mission concept features 12-16 small low Earth orbiters (LEOs) in two nested arrays of six planes each. The satellites, in circular orbits at 700 and 850 km, would make three types of measurements: 1) GNSS L-band atmospheric occultations to measure refractivity; 2) LEO-LEO crosslink occultations to observe water vapor absorption; and 3) GNSS ocean reflections to observe ocean height and state. The LEOs will track all visible GNSS occultations fore and aft and all ocean reflections having an incidence angle >15°. In addition, the LEOs will exchange crosslinks at 10, 14, 18, and 23 GHz. Crosslink occultations and GNSS reflection data will provide several complementary new measurements including precise global water vapor distribution from the surface to the tropopause and eddy-scale to mesoscale global ocean circulation with few-day resolution. AMORE also offers a rich source of "conventional" GNSS occultation data, more than tripling the acquisition of atmospheric temperature, pressure, density, moisture, and geopotential height data from currently planned missions.

Individual LEOs will exploit onboard GNSS navigation information to maintain a predetermined array configuration to allow full mission autonomy. A principal strength of AMORE is its concurrent or "synoptic" global sampling, in complement to the sequential sampling of typical single-platform observing systems. Near-uniform global coverage is reached within a few hours (and rapidly densifies thereafter), alleviating a number of sampling problems of conventional instruments and enabling new investigations. Examples include observing ocean eddy formation and evolution and the full diurnal atmospheric temperature cycle each day.

4.1 Principal Science Objectives

AMORE seeks to advance our knowledge of climate behavior and climate processes, and to test and refine climate models by:

- characterizing climatic behavior and variability
- measuring atmospheric and oceanic quantities affecting climate system feedback;
- quantifying the response of the atmosphere-ocean system to external forcings;
- further elucidating oceanic heat transport.

To address these issues the mission will continuously and synoptically observe:

- global water vapor distribution throughout the troposphere at <1 km vertical resolution;
- atmospheric temperature and geopotential heights from the surface to 85 km;
- precise atmospheric refractivity (and derived quantities) from 0 to 85-km altitude;
- global profiles of cloud liquid water;
- sea-surface topography and eddy-scale ocean circulation with near-daily resolution.

Further processing of refractivity data yields temperature, pressure, geopotential heights, and wind fields, from the surface upward; the bulk temperature of the troposphere; and (model-dependent) water vapor in the lower troposphere. High frequency AMORE crosslinks will directly measure water vapor concentration throughout the troposphere independent of other data or models. Further processing of sea-surface topography will yield both currents and heat fluxes due to eddies in the ocean mixed layer.

Several features distinguish AMORE from other sensors: Because all occultations begin or end above the atmosphere where bending is zero, each profile is self-calibrating and virtually unbiased; because limiting errors are effectively random, many refractivity profiles can be averaged to yield an equivalent temperature accuracy of ~0.1 K in a climate region of interest, or roughly an order of magnitude below that of more conventional techniques; GNSS occultation and reflection products are virtually unaffected by weather and clouds; Over 1,600 daily LEO-LEO links at 14-23 GHz will map water vapor in the upper troposphere to nearly 3 ppm, and will extend refractivity mapping from the 50 km altitude limit of GNSS to a maximum of about 85 km; LEO-LEO links at 10-14 GHz, together with thousands of GNSS occultations, will extend global water vapor mapping to the surface; reflected GNSS signals will provide ocean height measurements precise to a few cm (after massive averaging), achieving an average resolution of 25 km globally within 1 day.

The AMORE concept is distinguished by its unusually rapid global coverage. Figures 6 and 7 show the distribution of the 12,000 GNSS occultations and 1,600 crosslink occultations to be obtained each day. The near uniformity of the latter depends on the different altitudes of the two sub-arrays. Ocean reflection coverage is even more dramatic producing 16-20 million 1-second ocean height samples with 1 m precision every day.

4.2 Instrument Description

All science measurements are obtained with a single core instrument: an extended TurboRogue Space Receiver (TRSR) of the kind being flown on several upcoming international occultation flights, including CHAMP (Germany), SAC-C (Argentina), GRACE (US-Germany), and COSMIC (Taiwan-US). Apart from front end changes to deal with new frequencies and the addition of GLONASS tracking, the basic TRSR for AMORE would be little altered from flight proven models.

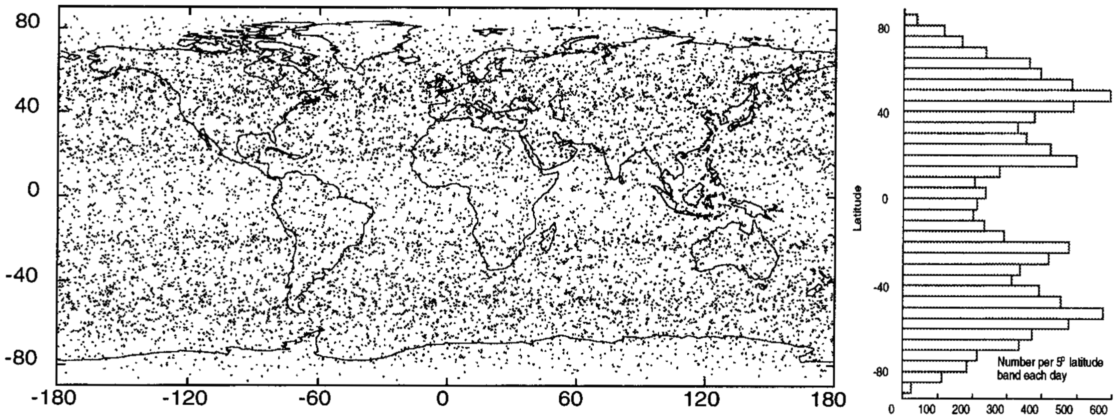

Fig. 6. Typical one-day GNSS occultation coverage with a 12-satellite constellation.

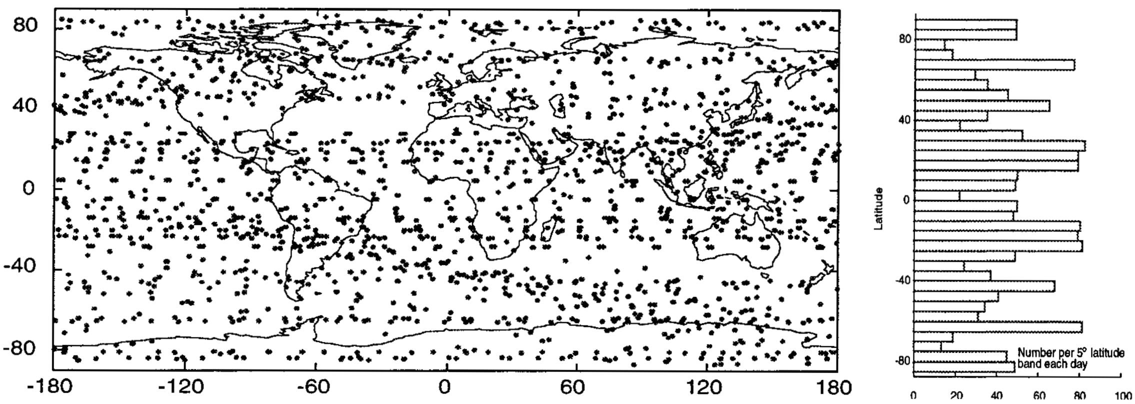

Fig. 7. Typical one-day crosslink occultation coverage with a 12-satellite constellation.

The receiver will perform similar functions on all signals: measure signal amplitude; compute pseudoranges; and measure precise carrier phase. Integral to the receiver is a high-speed microprocessor which will control all receiver operations, compute the onboard navigation solutions, and control the autonomous operation of the spacecraft.

The microwave crosslinks are engineered to survive the water vapor absorption. In the lower troposphere, where water vapor is abundant, we employ the less strongly absorbed 10 and 14 GHz signal. Transmitted power and receive antenna gains are sized to achieve a voltage SNR of 3,000 within 1 sec for a worst case moisture concentration of 20 g/kg at the bottom of the troposphere in the tropics. This will deliver a typical water vapor measurement accuracy of 4%. In the upper troposphere, where the moisture concentration is far lower, the prime consideration is detecting the weak effect with a precision sufficient for a measurement accuracy of 3 ppm. A frequency close to the 22.2 GHz water line is therefore essential. An instrument block diagram is shown in Fig. 8.

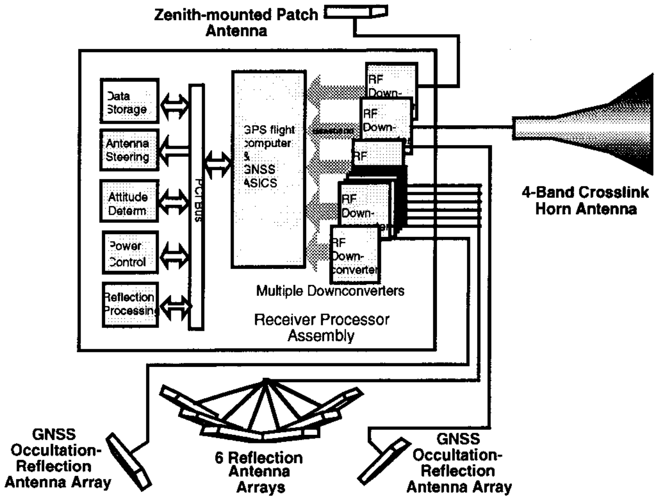

Fig. 8. *High level block diagram of the JPL TurboRogue GNSS occultation receiver.*

4.2.1 Refractivity from Phase

As the signals pass through the atmosphere they are retarded and bent, inducing a Doppler shift. The instrument continuously measures the carrier phase, from which we can isolate the atmospheric Doppler shift. From there we can determine the bending angle and, by applying a series of simple geometric assumptions and the ideal gas laws, atmospheric refractivity, density, pressure, temperature (or moisture), geopotential heights, and a variety of other products.

Refractivity is recovered with a vertical resolution of 0.5-1.0 km and a horizontal resolution of ~200 km. The fractional refractivity error of a single profile is 0.2-1.0%, due mostly to random error from atmospheric inhomogeneity; long-term averaging yields a fractional refractivity error of less than 3×10^{-4}. This translates into 0.1 K and 1 meter of temperature and geopotential height accuracy where water vapor is negligible (T<250K).

4.2.2 Altimetry with Reflected Pseudorange

Reflections received from low orbit are far weaker than the direct signals, typically by 30-40 dB. Analysis indicates that we require a downlooking antenna gain of at least 24 dB to acquire reflected pseudorange data with an average precision of 1 m over an integration time of 1 sec. This assumes coherent averaging of returns for 10 ms (after which the signal is decorrelated by ocean changes), followed by noncoherent averaging of 10 ms points into 1-sec normal points. The calculated footprint of the zone detected by a single lag on a GPS receiver at 800 km altitude varies from 5-20 km, depending on incidence angle. GPS reflection data obtained from aircraft have been studied by groups at Langley [12] and in France [13]. Recent studies by a research team at JPL of GPS reflections observed fortuitously by the SIR-C radar aboard the space shuttle support this analysis. Figure 9 shows what may be the founding event of space-based GNSS reflectometry: the first carefully observed ocean reflection received from space [14]. The sharply rising part of the graph provides a measure of the range; the long tail is the result of scattering about the specular point and provides information on surface roughness and other quantities.

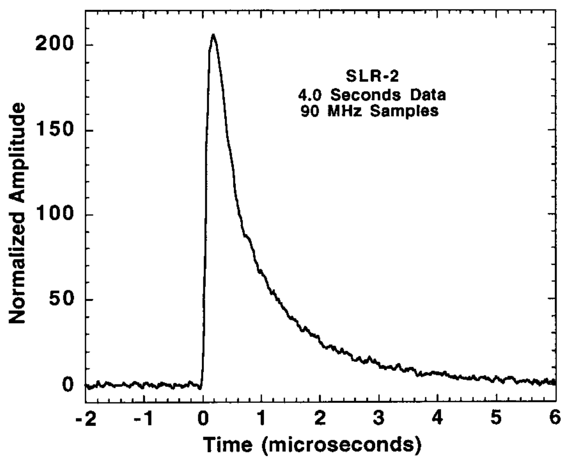

Fig. 9. *Amplitude of ocean-reflected GPS L2 signal viewed by the SIR-C antenna aboard the space shuttle [14].*

To obtain ocean height from reflected pseudorange we must accurately model the positions of the transmitter and receiver, and the effective reflection point. The first two are readily achieved at the few-centimeter level by established GPS techniques. The reflection point can be precisely determined by an iterative procedure which depends on modeling the nominal ocean surface through precise knowledge of the geoid and tides. Iterative adjustments to the nominal reflection point are made until incidence and reflection angles agree to within some tolerance (say, 0.1 mrad). Simulations show that 5-6 iterations will locate the point adequately to support useful ocean science.

The chief error source in ocean height, besides the system noise of ~1 m per normal point, is the delay from tropospheric water vapor. One can use models derived from occultations and other data to calibrate this delay. Alternatively, one can solve for ocean height and tropospheric delay together, though recent analysis by S. Wu at JPL indicates that this approach is considerably less effective.

4.2.3 Water Vapor from Crosslinks

Water vapor absorbs strongly at 22.2 GHz and considerably less strongly at lower frequencies. Changes in measured amplitude thus directly reveal water vapor distribution. In practice, moisture profiles will be recovered by combining phase and amplitude information. Phase enables determination of the atmospheric bending angle, and thus the path taken by each ray and its tangent height, permitting estimation of diffraction and defocusing effects. The amplitude measurements reveal the total extinction along the ray path. The unattenuated signal above the atmosphere is measured for calibration. The attenuation through the atmosphere then gives a direct measure of the amount of attenuating matter along the path. In the upper troposphere, where the moisture concentration is low, we employ the strongly absorbed 23 GHz signal; in the moist lower troposphere we switch to 10 GHz. In both cases 14 and 18 GHz are used. Environmental errors include defocusing due to atmospheric bending (derived from phase data), diffraction and scintillatons (estimated with a 2nd frequency), and signal absorption by other constituents such as O_2 (derived by reconstructing the atmospheric temperature-pressure structure). Atmospheric moisture will reduce the signal level by absorption and scattering; this will be calibrated with multiple frequencies.

4.3 Spacecraft Description

The AMORE spacecraft concept is derived directly from, and shares many subsystems with, the COSMIC occultation spacecraft now under development at the University Corporation for Atmospheric Research, in Boulder (see next section). The core science instrument, a GNSS receiver, serves as a multi-function spacecraft nerve center. In addition to acquiring science data, the receiver will determine real-time state, attitude, and time; provide onboard computing for all spacecraft operations; provide all onboard data storage; and receive and decode uplinks. It also features an integrated star imager for computing precise spacecraft attitude in real time. The spacecraft includes a power system, 3 reaction wheels, 3 magnetic torque rods, an inertial reference unit, an S-band downlink, and a hydrazine propulsion system.

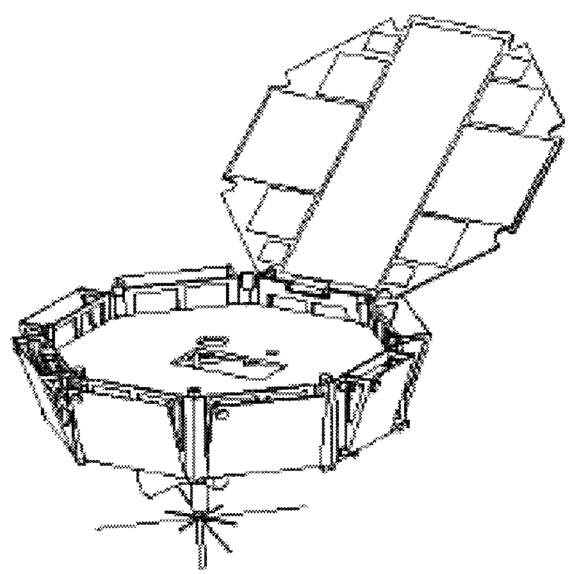

Fig. 10. *Sketch depicting a possible configuration for the AMORE microspacecraft.*

Figure 10 shows a sketch of one AMORE spacecraft concept. The solar panel opens to a fixed angle and is not articulated. There is a single zenith GNSS antenna to provide real time navigation and after-the-fact precise orbit determination. Each of the eight side panels holds 28 simple GNSS patch antennas, forming an electrically steered phased array for collecting GNSS ocean reflections. The antenna arrays facing in the fore and aft velocity directions also collect GNSS occultation data. Beam steering of the arrays, which provide over 20 dB of gain, is controlled by a dedicated processor derived from the processor in the GPS receiver. On the boom below the spacecraft is a horn antenna, which can pivot ±400 deg in azimuth for performing crosslinking between spacecraft. Below the horn is the antenna for a tri-band radio beacon, an ionospheric instrument being carried by COSMIC. Another COSMIC instrument, the Tiny Ionospheric Photometer, is mounted on the nadir surface. The orbital average power (OAP) consumption is estimated to be 110 W. The power allocated to the payloads is high for this mission, and can be quickly reduced for contingencies and power generation anomalies.

5. THE FUTURE OF SPACEBORNE GPS SCIENCE

Several upcoming international missions will carry versions of the JPL TRSR for atmospheric occultation. Indeed, the first two, the Danish Ørsted and the South African Sunsat missions, were launched in Feb 1999. Two more-advanced versions will fly on the German CHAMP and the Argentine SAC-C missions in early 2000. Both of these will attempt some ocean reflection measurements as well. More ambitiously, the first operational constellation, known as COSMIC, is planned for launch in Dec 2002. COSMIC, sponsored primarily by Taiwan with contributions from several US agencies, will comprise 8 spacecraft in 8 high-inclination planes. It will have a nominal mission life of 3-5 years and will demonstrate the operational utility of an occultation array.

Fig. 11. Concept for a pilot constellation of spaceborne GPS receivers for Earth science.

While these missions will do much to advance spaceborne GPS science and to estiblish its myriad possibilities, they will not in themselves establish an ongoing presence of large numbers of GPS sensors in earth orbit. It is the hope of the growing GPS earth science community that a permanent constellation of several dozen microsats will be sponsored either by government agencies or by commercial interests (eyeing a potential worldwide market in GPS weather products) in the near future. One such concept being developed at JPL, consisting of dozens of "sensorcraft" weighing only a few kilograms each, is depicted in Fig. 11. This could be the prelude to an array of hundreds of tiny, autonomous sensors continuously monitoring the global atmosphere and ionosphere three-dimensionally and mapping the global ocean topography, with high resolution in space and time, within one or two decades. GPS/MET and the current experimental occultation flights are making the long-term prospects for spaceborne GPS science extremely promising.

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